PROGRESS WITH COMMISSIONING THE ICRH SYSTEM FOR THE LARGE OPTIMIZED STELLARATOR WENDELSTEIN 7-X

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The ICRH system for the stellarator Wendelstein 7-X of the Max-Planck Institute for Plasma Physics in Greifswald, Germany, is designed and constructed in an intense collaboration between the Laboratory for Plasma Physics of the Royal Military Academy (LPP-ERM/KMS), the Institute INF-1/Plasma Physics and the Central Institute for Engineering, Electronics and Analytics (ZEA-1) of the Research Centre in Jülich, Germany under the Trilateral Euregio Cluster (TEC) umbrella and IPP-Greifswald. The final ICRH system aims to deliver RF power levels up to ~1.5 MW (depending on the density profile in front of the antenna) with pulse lengths up to 10 s [1, 2]. The antenna consists of two poloidal straps, where each strap is terminated by a pre-matching capacitor at one end, short-circuited at the other and fed at an intermediate position. The shape of the antenna is matched to the 3D shape of the Last Closed Magnetic Surface (LCMS) of the standard magnetic field configuration on W7-X, resulting in a variable curvature in toroidal and poloidal direction over the plasma-facing surface of the antenna. In addition, the antenna can be moved radially over max. 35 cm (with a speed ≤ 6 mm/s), and a gas puffing system is incorporated to puff gas in the region between the scrape-off layer (SOL) and the LCMS to locally improve the coupling. A reflectometer is included in the antenna box to measure the density profile in front of the antenna. The antenna box and strap material in its final form consists of stainless steel 1.4429 with a magnetic permeability μ_r<1.01, and with a minimal Co content.

After intensive tests on the achievable voltage stand-off of the antenna, the radial movement and vacuum specifications on a purpose-built test stand in the period 2020, the antenna was inserted in the plasma vessel in 2021 and integrated in the Wendelstein 7-X CoDaC system in 2022. The antenna was operated for the first time on Wendelstein 7-X plasmas in the experimental campaign OP2.1 (2023). A refurbishment took place in 2023, to install two new pre-matching capacitors and to repair a damaged feed-through. The antenna with two operational straps was tested for the first time in OP2.2 (2024).

In the first set of experiments (February and March 2023) only one of the two straps of the antenna was powered, because of a faulty pre-matching capacitor (and vacuum feedthrough), leading to operation with $k_{\|} \sim 0$. High power operation (above 500kW) was tested in plasmas with a magnetic field of 2.5 T. Plasma breakdown, using ICRH only was tested at a magnetic field of 1.7 T. In these experiments using the standard magnetic configuration in W7-X the LCMS was located at 17 cm from the first wall; the antenna-LCMS distance was about 10cm. The plasma consisted of ^{4}He with a minority of H. Over 500 kW of RF power was delivered in the first hours of operation – a world record short time – without hitting an upper limit for the RF voltages or currents in the system. Despite the unfavourable heating conditions ($k_{\|} \sim 0$), an increase of the plasma stored energy was seen at constant electron density, pointing to an increase in the plasma temperatures. Even though the Faraday Screen is omitted in this antenna, based on extensive experience on TEXTOR [3], operations went very smoothly, without first wall interaction and with impurity levels remaining low. Plasma breakdown experiments were also undertaken at the lower magnetic field of 1.7 T, leading to the successful creation of plasmas for the full duration of the ICRH pulse (~ 1 s) with about 300 kW RF power. After removal of the antenna from the W7-X plasma vessel minimal impact of these first operations on plasma was seen on the antenna: only a slight discoloration of the straps and box could be observed.

In the second set of experiments (October and November 2024), the technical commissioning of the two-strap antenna was successfully completed, and initial heating experiments with the two-strap antenna were conducted. Dipole and monopole phasing was tested on plasmas with a majority hydrogen concentration at 2.5 T, and the antenna was powered up to 450kW in pulses lasting up to 6 seconds (Fig.1) and up to 0.8MW for 2 seconds without any antenna breakdowns. RF modulation was also successfully tested in long pulses. In all experiments, the antenna was positioned approximately 10 cm from the last closed magnetic surface (LCMS). Prior to achieving successful RF power operation with the antenna, extensive conditioning was required, gradually increasing the power on the straps and repeating RF pulses until no breakdowns were observed. Between operational days, the antenna was maintained at around 80°C to keep the conditioning of the antenna as optimal as possible.

In all experiments with a properly conditioned antenna, high radiative power levels were observed, nearly matching the power launched by the antenna; thus, we were unable to increase the plasma stored energy. For H minority heating in ^{4}He plasmas, despite prior conditioning of the W7-X first wall with ECRH pulse trains in ^{4}He, hydrogen concentrations remained too high (above 10 %) for efficient core power absorption. Similar challenges were encountered when attempting ^{3}He minority heating in H plasmas. In all experiments, plasma radiation was predominantly observed on the outboard side, concentrated mainly in the island region in front of the antenna. The reflectometer was commissioned and delivers now routinely density profiles, which prove very useful for a detailed understanding of the operation of the antenna. Further RF heating experiments are planned for OP2.3 (February–May 2025) with reduced H concentrations below 10 % in ^{4}He plasmas, and results to be included in the upcoming paper. To obtain the required low H concentrations additional Ion Cyclotron Wall Conditioning (ICWC) is foreseen prior to the IC heating experiments, successfully demonstrated on W7-X in the last weeks. A new diagnostic tool is also planned for OP2.3 to enable a more accurate measurement of the ^{3}He concentration in majority H plasmas.

Plasma startup was tested using both dipole and monopole phasing on plasmas at 1.7 T with varying concentrations of ^{4}He and H. Line integrated plasma densities of several times $10^{18}m^{-3}$ were achieved with up to 400 kW power applied to the antenna straps (Fig.2).

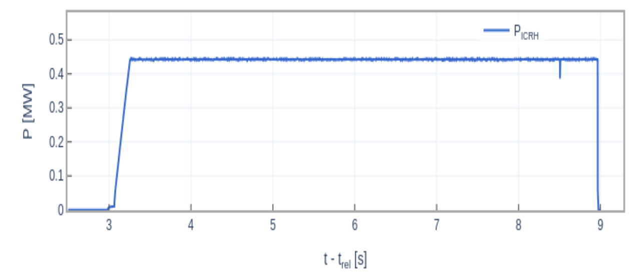

Fig.1: Example of a high power long pulse experiment (450 kW, 6s) without breakdowns at the antenna obtained with the two-strap antenna in W7-X (pulse no: 20241017.33)

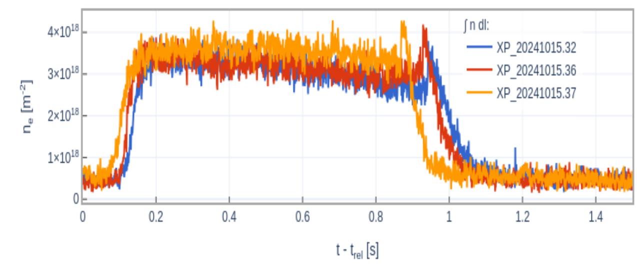

Fig.2: Line integrated plasma densities reached in plasma startup experiments (RF pulse length ~1s) with the two-strap antenna at 1.7 T and RF antenna powers between 200 kW and 400 kW.

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